EMBEDDED SENSOR SYSTEMS FOR SMART SHOES

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Approval sheet of the Thesis

This is to certify that we have read this thesis entitled **"Embeeded Sensor Systems For Smart Shoes"** and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

EMBEDDED SENSOR SYSTEMS FOR SMART SHOES

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The wearable technology is a promising field of research that can revolutionize the overall market of clothing. This can be done by giving the customers not just comfort and ease, but also more insight on their day-to-day activities.

The reason why these kinds of wearable technologies are being developed is because of the nowadays progress of the machine learning and artificial intelligence. Simply by wearing a piece of clothing, we can be able to receive actual data about the way we walk, run, stand and the state of our current health.

The main aim of this thesis is to explore smart shoes and the advancements that are currently being made in this rapidly growing section of wearables. The focus of this work is to create a smart device which will contain electronic chips that can be implemented inside the shoe heel counter. This will require an overall knowledge of different electronic components used such as: microcontroller, wireless interfaces, numerous sensors, and batteries.

There are two different ways that we can create and use such devices, active and passive. The main difference between them is that the passive mode does not require the usage of the batteries because it can use passive systems such as RFID tags and SAW sensors (Surface Acoustic Wave). It is in our best interest to use a passive system because by avoiding the need for batteries it can offer more energy-efficient smart shoes and, it would be the best solution for the environment and maintenance reasons compared to those with active systems.

Even though there are plenty of reasons to use a passive system, it is most likely that the different companies that will create the smart shoes, will use an active system.

This will happen because the number of features that a wearer wishes to have can be restricted by using a passive system, which will finally lead the market towards developing more battery-dependent wearables.

Keywords: *Wearable Technology, Smart Shoes, Active System, Passive System,*

ABSTRAKT

SISTEMET E INTEGRUARA TE SENSORVE PER KEPUCET E ZGJUARA

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Udhëheqësi: Assoc. Prof. Dr. Carlo Ciulla

Teknologjia e veshjeve të zgjuara, është një fushë premtuese kërkimi që mund të revolucionarizojë tregun e përgjithshëm të veshjeve. Kjo mund të bëhet duke u dhënë përdoruesve jo vetëm rehati dhe lehtësi, por edhe më shumë njohuri mbi aktivitetet e tyre të përditshme.

Një nga arsyet kryesore të avancimit të teknologjisë së veshjeve është zhvillimi i inteligjencës artificiale. Thjesht duke përdorur një veshje të zgjuar, ne mund të marrim të dhëna aktuale për mënyrën se si ecim, vrapojmë, qëndrojmë në këmbë dhe gjendjen e shëndetit tonë aktual.

Qëllimi kryesor i kësaj teze është të eksplorojë këpucët inteligjente dhe avancimet që janë duke u bërë aktualisht në këtë fushë. Fokusi i kësaj pune është krijimi i një pajisjeje inteligjente e cila do të përmbajë çipa elektronikë që mund të vendosen brenda shollës së këpucës. Kjo kërkon një njohuri të përgjithshme të komponentëve të ndryshëm elektronikë të përdorur si: mikrokontrolleri, bateri dhe sensorë të shumtë.

Ka dy mënyra që ne mund të krijojmë dhe përdorim pajisje të tilla, aktive dhe pasive. Dallimi kryesor midis tyre është se mënyra pasive nuk kërkon përdorimin e baterive sepse mund të përdorë sisteme pasive si etiketat RFID dhe sensorët SAW. Është në interesin tonë më të mirë të përdorim një sistem pasiv, sepse duke shmangur nevojën për bateri, ky sistem mund të ofrojë këpucë inteligjente më efikase në energji dhe do të ishte zgjidhja më e mirë për mjedisin në krahasim me sistemin aktiv.

Edhe pse ka shumë arsye të mira për të përdorur një sistem pasiv, ka shumë të ngjarë që kompanitë e ndryshme që do të krijojnë këpucët inteligjente, do të përdorin një sistem aktiv. Kjo do të ndodhë sepse numri i atributeve që një përdorues dëshiron të ketë mund të kufizohet duke përdorur një sistem pasiv.

Fjalët kyçe: *Teknologjia e Veshjeve të Zgjuara, Këpucët e Zgjuara, Sistemet Aktive, Sistemet Pasive,*

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CHAPTER 1

INTRODUCTION

Nowadays we are seeing a growing popularity of smart wearable devices such as fitness bands, smartwatches, and smart shoes. This is happening because the data processing and data analysis are advancing with the help of machine learning and artificial intelligence. Such advancements, brings the meaningfulness of the data to a new level and opens new markets.

During the past few years, there has been a growing interest in smart shoes in the footwear industry. We are seeing that the world's leading footwear companies like Nike, Adidas, Asics, and companies that are not mainly focused on footwear like Samsung, Lenovo and Xiaomi are devoted to produce new products that have in focus innovative shoes.

We wear shoes everyday so why not take advantage of this essential product? By combining the technology with shoes, we can use them not only to protect our feet but also to track, analyze, monitor, and provide us real-time personalized feedback. What if the shoe showed the wearer the chances of injuries that they might encounter while walking or running, some tips on how they can improve the posture which would lead in the avoidance of a lot of future problems?

Many of these questions were answered optimistically from the application perspective. However only some works exist discussing the sensor technology to achieve reliable, cheap, and sufficiently low energy demanding applications. In this thesis, the focus is going to be on the way that we can integrate small sensors that could fit in the heel counter of the shoe which would transform the shoe into a smart wearable device.

We begin the thesis by firstly, presenting a literature review of the current developments in the smart shoe market and then we provide an analysis of the electronic components used that will be embedded into the shoe. A detailed description of sensors parameters, sensor types, and their working principles is given, along with a detailed description of force, gait analysis, and pronation degree.

We also explore the different scenarios of our life that smart shoes would be beneficial. There are a lot of areas where smart shoes can help the wearer including sports, e-sports, entertainment, and medicine to name but a few. An overview of patents which are related to smart shoes and hold the latest data are included, which gives the reader a more accurate impression of what these companies are focusing on.

The energy storage is important in the functionality of the smart shoes. One of the widely used batteries in wearable devices are lithium-ion polymer batteries but we should keep in mind that over the past years, the flexible lithium thin-film batteries have attracted much attention. In this thesis, we will analyze two different scenarios which include microcontrollers, a Bluetooth interface, and sensors with two different batteries, first a conventional, rigid lithium-ion polymer battery and second, a flexible lithium thin-film one.

Even though nowadays in the smart shoes industry the active systems have been widely studied and applied, we will try to consider the usage of a passive system or specifically, radio-frequency identification technology. Finally, we evaluate further application ideas and the prospect of embedding sensors into completely passive systems such as surface acoustic wave sensors (SAWs).

1.1 Feasibility Study

The objective of my project is to create two different embedded sensor systems that can be implemented inside of the shoe. These systems will turn the shoe from normal to a smart wearable device. There are going to be some differences between the two systems where the first one will be active (where the batteries will be part of the setup) and the second one will be passive (where no batteries will be included).

These smart shoes can be helpful because they can predict potential chances of injury that might occur in the future simply by analyzing the walking or the running pattern of the person that is wearing the shoe. It can be beneficial for almost everyone because this smart wearable device can give tips on how the person wearing the shoe can improve the posture which would lead to the avoidance of a lot of future complications.

The final product will be a wearable device which will be implemented inside of the shoe heel counter and insole. Finding the optimal weight, size, position as well as power consumption, play a crutial role in the wearable prototype. The wearer will be able to check and analyze all the results gathered from the smart shoe.

CHAPTER 2

LITERATURE REVIEW

2.1 Shoes Setup

One of the most necessary products we wear in our everyday life is the shoe. Despite this fact, there are only a few people who wonder how the shoes are produced. There are several manufactering steps, shoe parts, as well as materials. There is a wide variety of materials used in shoe production, due to their specification for certain shoe types (sport, boots, sandals,etc.). Footwear comfortability, injuries protection, or shoe appearance are considered as essential criteria in the material selection.

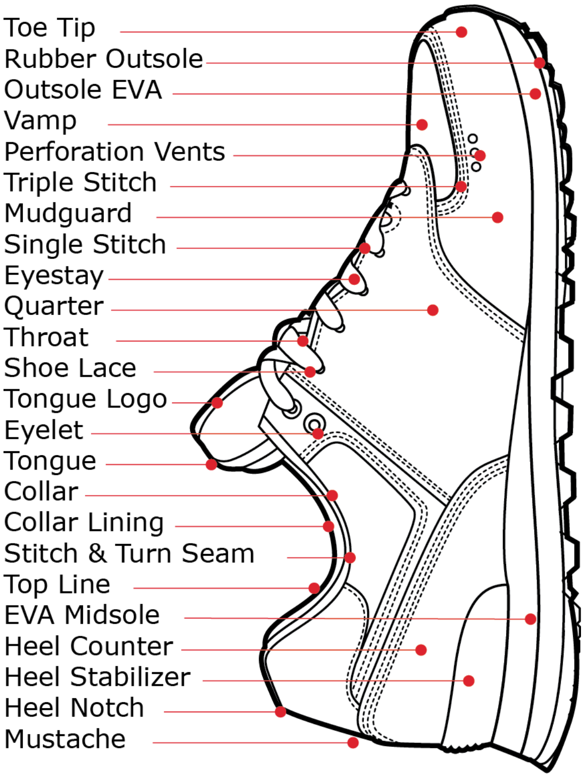

Figure 1. Shoe setup [1]: The most important parts to our research are the heel counter and midsole, where sensor integration is most feasible

Shoemaking can be considered a handicraft profession. As shown in (*Figure 1*), there are many different parts in a shoe such as a heel counter, insole, midsole, outsole, vamp, etc. Some of them are explained as follows:

Heel counter, positioned between the lining and upper, maintains the shape of the shoe and helps strengthen the rear of the shoe.

The heel is known as the part of the sole that raises the rear section of the shoe in relation tothe front.

Sole is the shoe part that sits below the wearer's foot. It is usually constructed of several layers, such as *insole, midsole,* and *outsole*.

Depending on the selected production method and the manufacturer, the number of steps needed to make a pair of shoes varies from 68 up to 390[1]. Nowadays, due to modern machines' development, the time needed for the production of a pair of shoes is reduced.

2.2 State of the Art

The research in IoT sensors, battery and smart materials has played a crucial role in evolution of smart wearable technology. All the wearable devices are gaining an important role in our everyday life. A surge in demand of smart shoes has been realized in the recent years, especially in sport and health sector.

A smart shoe is an interactive shoe, with hardware and software components embedded, that is constantly providing the wearer with personalized feedback.

The state of the art of a smart shoe is considered a shoe with a smart insole, where gait analysis, number of steps, posture, pressure distribution, health checks and real time feedback is provided. AI and ML algorithms combined with all the sensors inside the shoe and based on the wearers data, advice the wearer with crucial information to improve their life. To avoid discomfort when walking, a perfect design of sensors and other electronic components embedded in the shoe insole must be considered. The weight and size of high-spec sensor modules and all other elements must be light and small so the wearer would not notice the difference from a normal shoe.

2.2.1 Related Work

In this thesis, a thorough research with the most important patent available and companies which have already a product in the market, is provided.

There are a lot of companies researching to achive the state of art for a smart shoe. Big names like, Nike, Adidas, Puma, Google are investigating to be the first to achieve the next break through in wearable technology. A typical example of a smart shoe is explained in [2]. Nowadays, the most of smart shoes contain a battery inside and provide different features like step measurements, insole pressure meassurment like shown in [3][4][5][6][7][8][9][10][11][12][13][14][15][2][16]. These features start from the most basic ones as shown in [7], [9] and [17] and continue to the really fancy and high-tech ones as shown in self-lacing shoes from Nike [6]. The main application field of smart shoes is in sport, due to the importance of the feedback provided from the smart shoe app. The wearer can get a detailed analysis of all the data gathered from the walking or running and work harder to improve the performance [13]. Increasing the battery capacity in order to allow longer battery life is still a challenge in this industry, but different futuristic ideas are being presented everyday where we can mention [18]. This new concept improves the lifetime and significally reduces the shoe weight making it even more compatible for the wearer. The wide opportunity of features is possible due to IoT sensors embedded in smart shoes. The basic principles of acceleration, pressure, magnetic, temperature sensors are provided in [19], [20], [21] and [22]. Google, Samsung and some other companies are providing accurate and high-tech AI and ML algorithms which can use the data from sensors and provide a personalized output to the wearer as shown in [5] and [13].

Another important application of smart shoes is health. It has been shown from different papers that there is a pure connection between the way we walk and different neurological disorders such as parkinson, diabetis and multiple sclerosis. A detailed information is provided in [23][24][25][26][27][28][29][30][31][32][33][34]. As mentioned in [23] and [30]vv, it is really important to check the pressure distribution while walking in order to prevent people suffering from diabetes from cevere feet complications. In [31], [32], [33] and [34] it has been showed that smart shoes play a huge role in detecting people who might suffer in the future from Parkinson or multiple sclerosis just by analyzing the way the wearer walks.

As part of this thesis, a possibility of smart shoes with RFID and passive sensors is provided. RFID technology is well-known and not a new concept, but different companies such as Rhenoflex is trying to integrate it in smart shoes. A more detailed information about the RFID technology and its application is presented in [35][36][37][38][39][40][41]. In [42] and [43] SAW sensors are explained and a possibility for combining the RFID and SAW sensors in smart shoes is proposed as part of this thesis. As described, the features measured from this combination are not comparable with the shoes containing a battery, but it is still worth researching.

CHAPTER 3

PASSIVE SENSORS AND RFID

3.1 Introduction to SAW Sensors

Surface acoustic wave (SAW) radio sensors are small devices that enable remote measurement reading, making them suitable for a variety of sensing applications.

It is true that packaged SAW filters are insensitive to external stimuli such as stress, humidity,electric and magnetic fields, etc., but their many advantages such as free maintenance, no power supply requirement, possibility of wireless installation, small aging rate etc., have fueled research on their usability, and they have been found significantly valued in the sensors field.

With the appropriate mounting, packaging technology, or coating, SAW devices can sense temperature, pressure, force, and acceleration, to name but a few.

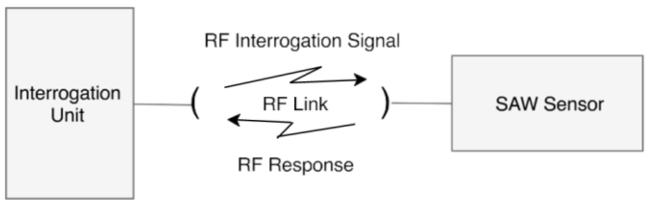

Figure 2. Block diagram of a wireless sensor system based on passive SAW sensors

3.2 Working Principle of SAW

SAW devices function due to piezoelectricity, the physical phenomenon which describes the change in the material's electrical properties when mechanical stress is applied, and vice versa.

The transduction between the electrical signal and the acoustic wave in SAW sensors is attained with the help of an interdigital transducer (IDT), which consists of two interlocked comb-like metal structures deposited on the piezoelectric substrate.

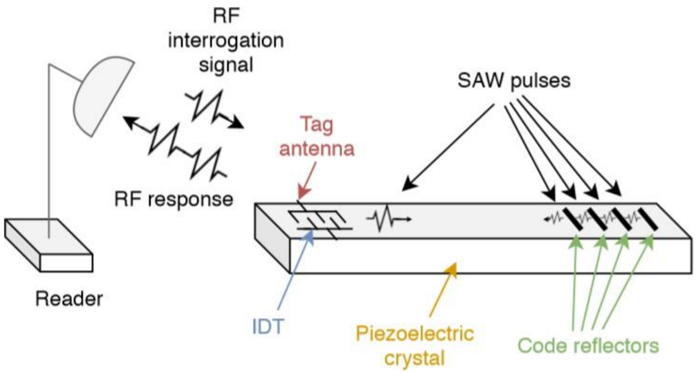

Figure 3. Passive SAW device layout

A reflector-based SAW tag is depicted in (*Figure 3*), where one can observe the interrogation pulse, emitted by the reader, and received by the tag antenna which is connected to an IDT. The IDT does the transformation of the electrical signal to an acoustic wave of a nano-scale –a mechanical wave of particle displacements. The generated SAW pulse then travels across the surface of the piezoelectric (usually lithium niobite – LiNbO3) substrate, to be reflected and transmitted partially by the so-called code reflectors (one or more aluminum strips) contained in specific positions on the chip.

It becomes clear that the reflected SAW traveling back to the IDT carries a code based on thereflectors' positions and time delays of the reflected pulses. This encoding method is known as time position encoding or pulse position modulation (PPM). When the pulses return to the IDT, the signal is converted back to electrical, retransmitted by the tag antenna, and decodedby the reader [10].

3.3 Sensor Applications

SAW sensors, as mentioned previously, can be sensitive to varying levels of stimuli from different physical parameters, when coated with materials that undergo changes related to thedesired physical parameter of measurement. By applying a wave on the IDTs, the surface acoustic waves are simulated. There are several parameters relevant to the wave properties,such as the substrate material, IDTs shape, and the deposited material on the piezoelectric substrate. The main parameters in the sensing application of SAW sensors are the wave speed and wavelength. The greater the wave speed, the lesser time is needed to transmit from one IDT to another. The wave velocity changes with a change in the temperature or theanalyte concentration. The sensitivity of a SAW sensor increases with the increase inresonance frequency, which translates to high wave speed and small wavelength.

Some of the more prevalent SAW sensor applications are described as follows.

3.3.1 Pressure Sensors

Pressure sensors consist of the first SAW application in sensors, dating in 1975. A SAW pressure sensor is attained by turning the SAW device into a diaphragm because SAW velocities are strongly affected by stresses applied to the piezoelectric substrate. Slight fluctuations of pressure, humidity, or mass loading, influence the way the acoustic wave propagates in the SAW sensor. These sensors have several advantages such as low cost, small dimensions, lightweight as well as passiveness and wireless functioning. A technology with excellent results that features SAW pressure sensors is its integration in a car tire, leadingto improved safety, greater fuel efficiency and longer tire life[9].

3.3.2 Mass Sensors

The physical parameter that SAW are most sensitive to is mass. Due to this fact, there is several applications for mass sensors such as particulate sensors and film thickness sensors. Particulate sensors are attained by coating the substrate with an adhesive substancesuch that any particle that meets the surface remains there and perturbs thewave propagation. The mass changes, as well as most of the factors affecting the wave speed,are mostly evaluated by fabricating a kind of resonator and measuring its resonance frequencychange. The Sauerbrey equation describes the idea behind the

SAW mass sensor. It defines the linear relationship between the resonance frequency and mass loading, as showed in Equation (1) [22].

$$\Delta f = \frac{2f_0^2 m}{n(p\mu)^{0.5}} = -C_f \Delta m \qquad \text{(Equation 1)}$$

Where:

Δf is the frequency change, Δm is the mass change, f_0 is the resonance frequency, ρ is the density, μ is the shear modulus of quartz.

These kinds of sensors are widely used in cleanrooms, air quality monitors, and atmosphericmonitors[44].

3.3.3 Bio and Chemical Sensors

"An electrochemical biosensor is a self-contained integrated device, which is capable of providing specific quantitative or semi-quantitative analytical information using a biological recognition element (biochemical receptor) which is retained in direct spatial contact with an electrochemical transduction element." [45]Biosensors can detect chemicals in liquids. This effect is created with yet another special coating that can absorb specific biological chemicals.As known, a thin layer is deposited on the piezoelectric substrate, where the SAW is propagated. The formation of this layer can change the SAW wave speed. A difference in either the electric field or mass loading is observed when analytes interact with the thin layer. Thus, the gas, biomolecules, chemicals, etc., are sensed either by observing the conductivityof the thin layer or the mass changes when absorption of specific molecules occurs[44].

3.4 Introduction to RFID

Radiofrequency identification (RFID) is considered as the set of all technologies that use radio (electromagnetic) waves to identify and track tags attached to or incorporated into different objects. Since the '70s, its applications have evolved rapidly, and its usage has increased in such a prompt way in various daily-life applications [37].

A very popular application dating from early 2000 is pet identification via an IC chip, injected under the skin of an animal body. This microchip has the size of a large grain of rice and couldeasily be injected by a veterinarian. This technology proved to be extremely useful in the process of retrieving lost pets, all thanks to the unique ID chip containing all the necessary information regarding the pet's identity and owner. Another enormous contribution of RFID was the improvement of inventory tracking and management efficiency by attaching an RFID label to all shipments. Due to these and many other advantages, the usage of RFID has become critical in different fields such as goods and gadgets tracking in shops, public transportation tolling systems, payment via mobile phones, etc.

Some of the big advantages of RFID technology are flexible distance reading and identification tag accuracy. Furthermore, up to several megabytes can be saved in the tags' memory butnot only- the memory itself is rewritable which means that the data can be stored, modified, or deleted as per user requirements. There are three types of RFID tags: passive tag, semi-passive tag, and active tag.

3.5 Components of RFID Systems

There are two main components in the RFID system:

- RFID tag
- RFID reader

3.5.1 RFID Tag

An RFID tag is designed to be attached to or incorporated into an object, and this is the reasonit generally comes in a very small size. There are two main components in an RFID tag: a microchip and an antenna. The microchip, or "the heart of the tag" serves to store the identification data, whereas the antenna receives the signal transmitted from the reader and sends back the data to the microchip. In (*Figure 4*), the signal transmission process and the respective components are depicted for different types of tags.

Passive tags consist of neither battery nor radio transmitter. The electrical power required forthe circuitry and the microchip to operate is received from the reader. The communication fromtag to the reader is provided through a backscattered signal. No need for batteries in these tags makes them affordable, durable, and small in size, but the main drawback is the limited range of communication. This RFID type of tags is the most popular amongst the three.

Semi-passive tags have no radio transmitters, but they contain their electrical power source. Like passive tags, the tag to reader communication is provided via a backscattered signal. The advantage of these tags over the passive ones is the increased range of communication due to batteries. On the other hand, the main drawback is that size and pricetend to go up as well. Active tags have their batteries and antennas, which leads to a broad range of communication.These kinds of tags can also have different sensors inside, but the major disadvantages are the high price and the large size

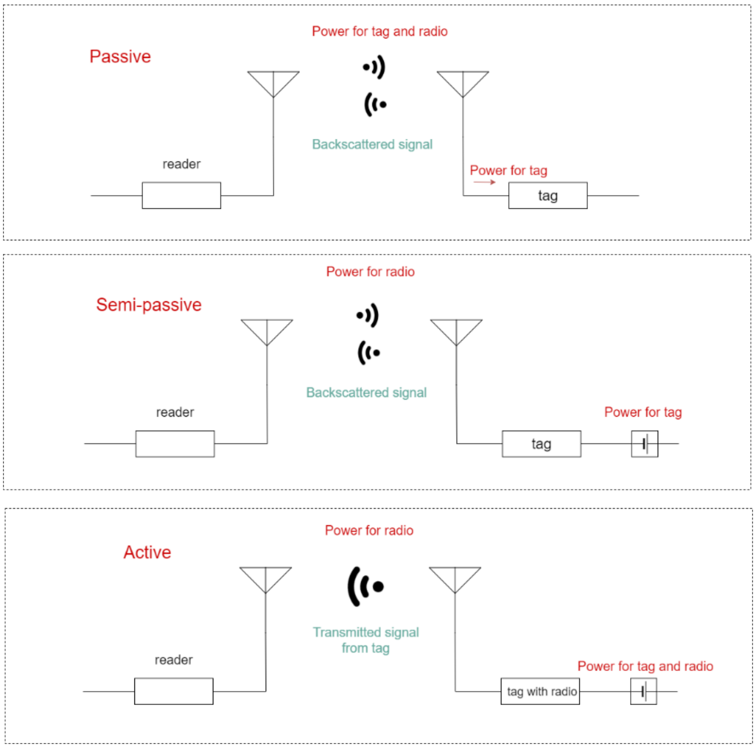

Figure 4. Different types of RFID reader-tag communication, classification by power-supply: passive tags obtainpower wirelessly, active tags have built-in power supply, semi-passive tags obtain power wirelessly but store power internally

3.5.2 RFID Reader

The reader is a radio transceiver: a device comprising both a transmitter and a receiver whichshare common circuitry and a single housing. [38] An RFID reader contains its antenna and power supply and is used to communicate with the RFID tags. After the information has beencollected from the tag, the reader can manage the information with the help of a connected computer or a microcomputer. It is essential to mention that the reader can communicate withthe tags with or without a line-of-sight propagation.

There are two well-known classes of RFID readers: read-only and read/write. Intuitively, one can distinguish from the name that the read-only readers can only read the information stored

in the tag. Due to this reason, they are widely used in passive tags systems. On the other hand, the read/write reader can modify the data in the tag, but the tag must have a re-writablememory.

An RFID reader can be fixed in a particular place or embedded in PDA (Personal Digital Assistant-electronic handheld information device).

CHAPTER 4

ACTIVE SENSORS

4.1 Sensor Basics

The name sensor comes from the Latin word "sensus", meaning sense. Although, in engineering, there can be found numerous definitions depending on specific devices. In our daily life, the term "sensor" defines an inexpensive but reliable measuring element, which is suited for high volume production. On the other hand, the formal definitions of a sensor from ISO (International Standards Organization) and DIN (Deutsche Industrienorm) respectively, consist of:

"Sensor is a device that observes and measures a physical property of a natural phenomenon or man-made process and converts that measurement into a signal"

"Sensor is the primary element in a measuring chain, which converts a variable (general non-electrical) input into a suitable measuring (signal, especially electrical)."

It is essential to differentiate a sensor from a transducer – sensors are a subset of transducers. A transducer converts a form of energy, which might be mechanical, thermal, electrical, etc. into a different one. To deal with the complexity of sensors, it helps to make a classification interms of quantity. As shown in Table 1 and as known from physics, the real world can be described by these seven basic quantities: length, mass, time, current, temperature, radiation,and concentration.

Table 1. Real-world fundemental quantities.

Quantity	SI base unit	Derived quantity
Length	m	Force (kg · m · s^{-2})
Mass	kg	Pressure (kg · m^{-1} · s^{-2}) Acceleration (m · s^{-2})
Time	s	Velocity (m · s^{-1})
Current	A	Voltage (kg · m^2 · A^{-1} · s^{-3})
Temperature	K	Heat capacity (kg · m^2 · K^{-1} · s^{-2})
Luminous intensity	cd	Luminance (cd · m^{-2})
Amount of substance	mol	Concentration (mol · m^3)

The combination of some quantities, such as length, mass, and time, leads us to other derived quantities such as force, pressure, and acceleration. The same quantity can be measured utilizing different physical effects and different sensors, but it is proven that relying on time yields the best results. From all the given quantities, time can be measured with the highest accuracy.

4.2 Acceleration Sensors

As known from physics, acceleration is considered a vector quantity, having both direction and magnitude. Acceleration is defined as a measure of how fast speed changes, or as the rate at which an object changes its velocity with respect to time. The accelerometer is the sensor used to measure acceleration.

4.2.1 Working Principle

The working principle of an acceleration sensor is based on the First Newton's Law stated as:

An object at rest stays at rest, and an object in motion stays in motion with the same speedand in the same direction unless acted upon by and external force. [19]

The working principle of these sensors is also related to a harmonic oscillator which can bedefined as:

A harmonic oscillator is a system that, experiences a restoring force F proportional to thedisplacement x when displaced from its equilibrium position:

$$F = kx \qquad \text{(Equation 2)}$$

Where, as showed in Equation (2) [22].

F is the force, k is the spring constant, x is the movement of the sensor (seismic mass).

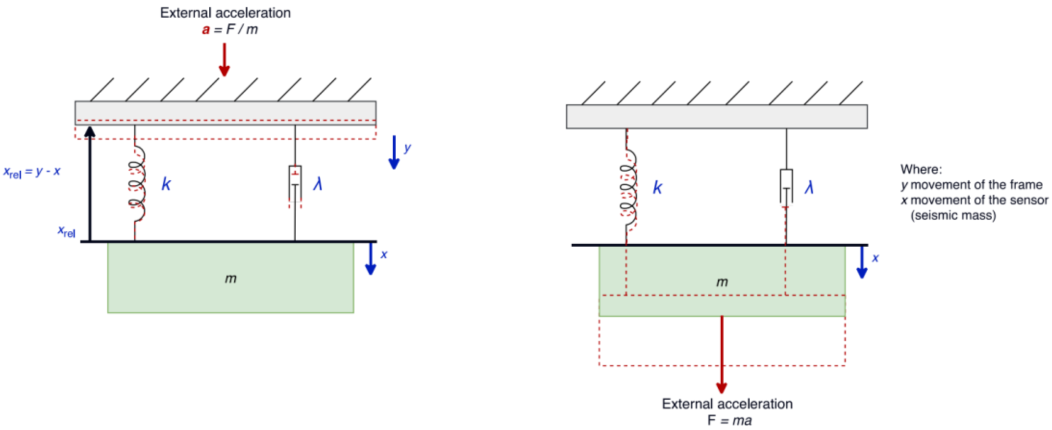

Figure 5. Working principle of the acceleration sensor

As viewed in (*Figure 5*), a mass, a spring, and a damping element are crucial components of the system, which helps in understanding the sensor working principle.

The sensor mass (m) is independent of the environment. The mass is coupled with the framevia a spring. As represented by the red arrow on the figure on the left-hand side, if there is a force applied onto the housing exterior, the sensor mass will not be affected. A movement of the frame with respect to the sensor mass can be observed, due to which, a movement of themass occurs.

4.3 Capacitive Accelerometer

This sensor operates based on the spring-mass system working principle. As shown on the left side of (*Figure 6*), in the comb structure, there are two fixed points, a beam, fixed outer plates, and the oscillating mass. On the right side, acceleration is applied in the left direction,so the fingers attached to the beam move closer to a fixed outer plate. This movement is proportional to the applied acceleration.

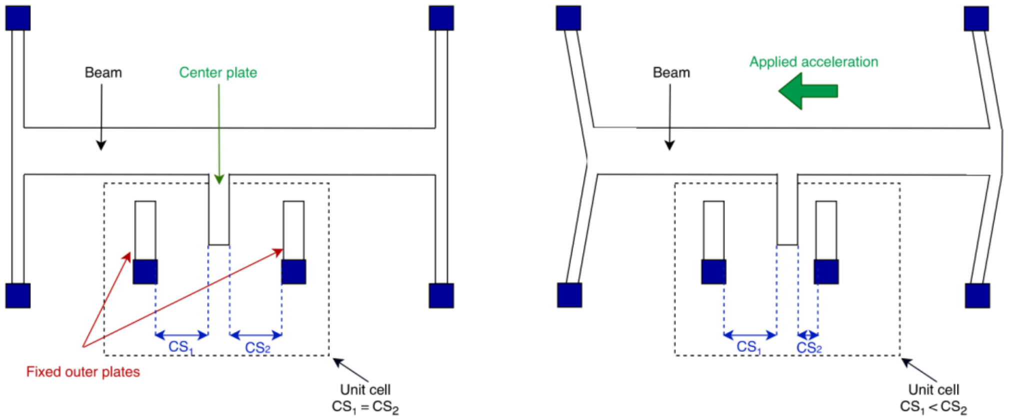

Figure 6. Working principle of a capacitive acceleration sensor

As depicted above, between the fingers and fixed outer plates, a differential capacitor is formed. Thus, if the mass moves to one side, the distance between the capacitor plates will reverse-proportionally change. It is essential to mention that the dimensions of the capacitors and the mass are defined from the micromachining process; only the cantilever design can becontrolled without affecting the design of the capacitive part. By changing the thickness of thecantilever, the sensor sensitivity can be adjusted from a 5 g to a 50 g beam.

The two capacities (CS1 and CS2) are excited by a rectangular voltage with a phase-shift of 180° between the signal at CS1 and CS2. Whenever the beam is deflected, a voltage proportional to the change in amplitude is generated after demodulation. A feedback loop is needed to electrostatically counteract the movement and keep the beam at rest independentof the actual acceleration. The sensor output is provided by the feedback signal.

4.4 Pressure Sensor

Pressure definition: Pressure as a measured quantity is defined as the applied force by a liquidor gas on a surface of an object. The pressure is usually measured in units of force per unit ofsurface area. Standard units are Pascal (Pa), Bar (bar), N/mm^2 or psi (pounds per square inch).

A pressure sensor is a device with an embedded pressure-sensitive element in it, and the actual pressure applied to the sensor is firstly determined and then converted into an output signal.

4.4.1 Types of Pressure Measurements

Pressure sensors are classified from a variety of properties, such as the type of pressure theymeasure or the operating temperature range.

Different pressure types are pictured and explained below:

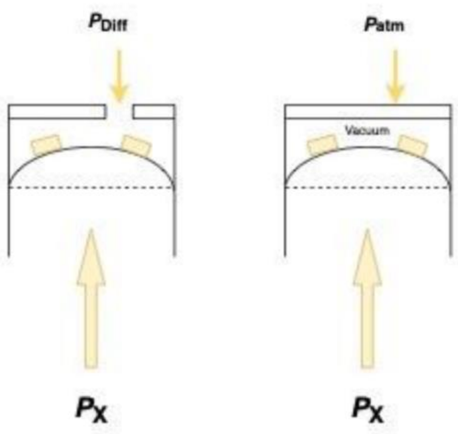

Figure 7. Principle of differential (left) and absolute pressure sensor (right)

- **Differential pressure sensors** determine the difference between two pressures. Pressure drops measurement, fluid levels, and flow rates measurement can be someapplications of pressure sensors.

- **Absolute pressure sensors** detect the pressure relative to a reference chamber (nearly vacuum so it can be considered as a pressure equal to 0 Pa). There is a significant advantage of these sensors- they remain unaffected by both temperature and pressure changes due to always measuring against the same reference pressure (vacuum).

Different technologies and working principles are used for accurate pressure measurement. Some of these principles are highlighted in the following section.

4.4.2 Piezo-Resistive Pressure Sensors

Piezo-resistive pressure sensors are the most common types of pressure sensors. As a resultof applied pressure, the strain is detected by the integrated strain gauges. A wide range of applications is suitable for these sensors, due to their robustness and simplicity.

The basic working principle of these sensors is the usage of a strain gauge made from a conductive material that, when stretched, it changes its electrical resistance. The strain gaugemay be attached to a diaphragm that recognizes a resistance change when the sensor element is deformed. This change will be converted into an output signal.

It is worth mentioning the three separate effects that contribute to resistance change of a conductor:

Stretching increases the resistance because the resistance of a conductor is proportional to its length.

As the conductor is stretched, its cross-sectional area is reduced, which leads to an increasein the resistance. When stretched, the inherent resistivity of some materials increases. [46]

The piezoresistive effect varies significantly between materials. The gauge factor specifies thesensitivity. Gauge factor is defined as the relative resistance change divided by the strain, as showed in Equation (3) [22].

$$\boldsymbol{GF} = \frac{(\frac{\boldsymbol{\Delta R}}{\boldsymbol{R}})}{\epsilon} \qquad \text{(Equation 3)}$$

Pressure Sensing Elements

The strain gauge consists of either metal or semiconducting material. The resistance changein metal strain gauges is mainly due to the change in geometry wherein semiconductors, thispiezoresistive effect dominates. Usually, the gauge factor in metals varies from 2 to 4, which means a change in output around 1 mV for each volt of excitation. On the other hand, the semiconductors gauge factor ranges from 100 to 200, meaning that the output signal is approximately 10 mV/V.

Function

A Wheatstone bridge circuit is used to measure the changes in the sensor resistance. An excitation voltage is provided to the Wheatstone bridge. The output voltage will be 0 V in the absence of stress, and when all the resistors in the bridge are balanced. A small change in pressure will cause a change in resistors in the bridge, which corresponds to an output currentor voltage.

4.5 Block Diagram of the Active System

A typical block diagram of an active system with all its components is presented in the following picture. All the sensors are serving as inputs and transferring the data to the Arduino board. This data is later analysed and can be presented either directly from Arduino serial monitor or via third-party application, thinger.io. While using thinger.io different widgets can be applied to visualize the output data collected from exceleration and pressure sensors with the help of graphs.

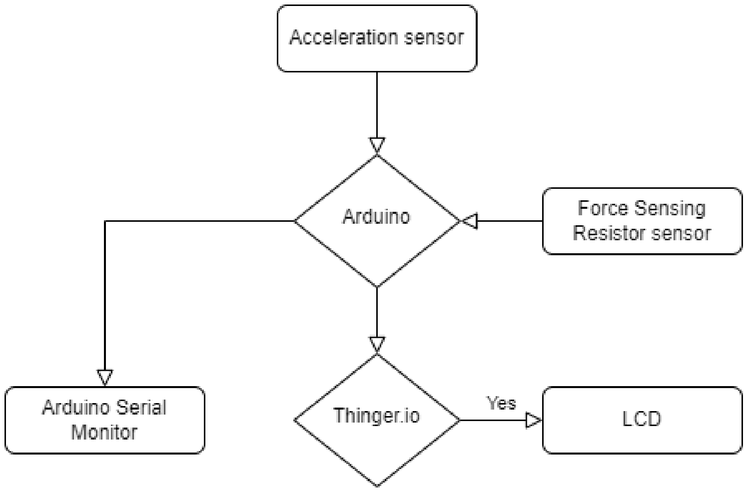

Figure 8. Block diagram of the active system

CHAPTER 5

APPLICATIONS

In this chapter, we are going to focus on the applications ideas for smart shoes, some of which have already been realized by different companies.

Regarding passive systems, besides SAW sensors integration applications described in detail in chapter 4, applications are restricted to RFID tags, with only a limited number of functions mentioned as follows.

There are different types of RFID passive tag memories, such as read-only, read-write memory, etc. Depending on the working frequency and types of tags, passive RFID tags can store from 2 kB up to 65 kB amount of information. In the military, there exist passive tags where storage memories can reach up to 128 kB.

Some application scenarios where information stored into passive RFID tags might be a considerable help in the footwear industry are presented below.

Providing information to distinguish between shoes made for left or right feet during:

- fabrication steps
- boxing a sold pair of shoes in the warehouse or in the shop

Recently, people have increased their awareness towards environment protection, which is being reflected in all applications. For instance, an excellent application where the environmental-friendly companies are combined with the footwear industry, is embedding a passive RFID tag full of general information into the shoe. This general information is providedfrom the companies where facts regarding the materials, and their recycling steps are stored into the tags.

On the other hand, active systems have many more applications compared to passive ones.The most important ones are the focus of this chapter, described in sections 5.1-5.3.

5.1 Sport

Physical activity has high importance in everybody's life. It can improve health and reduce the risk of developing several diseases. Keeping fit makes the whole organism work better, from the cardio-vascular machinery and digestion to every joint and vein in our body. Improving life quality and other immediate or long-term health benefits such as better concentration, creative thinking, problem-solving, as well as the stress-coping, are the benefits of regular physical activity.

Nowadays, the modernization trend of smart wearable is growing popular day by day. Smart wearable devices such as a smartwatch, fitness band, and recently smart shoes are becoming a necessity due to their high impact in our everyday life.

A smart shoe is a specially engineered shoe where detecting sensors, wireless charging and LED lights are placed. It allows the full shoe evaluation of the user body. Thus, it can recommend suggestions in a mobile app or a different output device. Smart shoes can analyze parameters such as: which part of the foot touches the ground initially, if the person wearing the shoes is a pronator or a supinator and if the user's stride presents any injuries possibility as well as the wearer walking efficiency and performance. By analyzing all these parameters, the shoe advises the wearer how to reduce fatigue, shows them the chances of injuries while walking/running, and gives them tips on improving posture and positions.

Different sensors are located at different parts of the smart shoe, such as at the soles, heel, or the heel counter. A wide diversity of sophisticated sensors such as pressure, acceleration, temperature, magnetic, etc. are embedded into the shoe. Furthermore, different shoes provide real-time location of the wearer due to a location tracking sensor. Some shoes can tell whether the wearer is walking/running in a flat/incline/steep surface, which brings another exciting feature of smart shoes, the counting of burned calories.

An overview of sensor types and their purpose is provided as follows:

- Accelerometer, gyroscope, and magnetometer are used for gait analysis.

- The main satellite navigation system, GPS, but also Galileo, and Glonass, provide a real-time location.

- Information about body weight distribution on the sole of the foot is provided by pressure sensors.

- Data acquisition for activities depending on altitude and the surrounding environment is provided from ambient environmental sensors such as light, sound, and atmospheric pressure sensors.

- Sensors provide the necessary information for the internal status regarding battery and memory capacity.

Another factor that is quite often underestimated from the wearer is the shoe cushioning. Some smart shoes provide the cushion monitoring feature, and in case of deterioration, the mobile app connected to the shoe sends a notification/alerts as well as recommendations for the new insert. Features as self-lacing have come true, and all the wearer must do is to press a button. Smart shoes will adjust and tighten the shoe according to the wearer's feet.

All the data recorded from all sophisticated sensors must be analyzed, stored, and transmitted via a reliable system. Next, filtering, drift correction, or descent-based algorithms get the relevant information form the raw sensor data. After data segmentation, the neccesary gait or activity patterns information can be extracted and analyzed for visualization, personalized feedback, and various health applications.

5.1.1 Important Walking and Running Parameters

5.1.1.1 Gait Analysis

Gait analysis is essential to analyze and quantify the wearer’s walking/running. The involvement of each body segment determines the gait speed. When walking with average speed, the lower extremities are involved primarily, followed by trunk and arms, which providestability and balance. The contribution of the upper extremities and trunk for balance, stability,and propulsion increases with the increase of the walking speed.

The gait cycle consists of the in-between movement of two consecutive foot-floor contacts, where the foot is not switched. It is also considered as a repetitive pattern of steps and strideswhere the step is a single step and stride is the whole gait cycle. The gait cycle consists of two main phases, the stance (60 % of the gait cycle) and the swing phase (40 % of the gait cycle). The stance phase consists of the entire time that the foot is on the ground, while the swing phase consists of the time that the foot is in the air [47].

The most accurate approach of the gait cycle recognizes eight phases consisting of three tasks. A short explanation is presented below:

The first task is the weight acceptance (0-12 %). Its objectives are limb stabilization, shock absorption, and body progression preservation. This task is broken down into **initial contact** and **loading response** phases. Initial contact is the first rocker of the gait cycle where the heel strikes the ground, and to preserve progression, the rotation over the heel to foot flat initiates. During the loading response phase, as the foot falls flat on the ground, stabilization of single-limb support is necessary, so the knee is slightly flexed to absorb shock.

The second task is single limb support (12-50 %), where body progression over the foot and the weight-bearing stability are analyzed. The third phase is **midstance**, where the forward progression of gait is maintained. The shank rotates forward over the supporting foot, and thesecond rocker motion of the cycle is created. In the fourth phase, the **terminal stance**, the center of the mass advances out in front of the supporting foot. The third rocker motion of thecycle is created when the heel raises off the ground as the roll onto the ball of the foot happens [47].

The last task is the swing phase (50-100 %), where the foot clearance over the ground, the limb forward swing, and the stance limb preparation are observed. This task can be broken down into four phases:

Pre-swing, which is the transition phase between stance and swing. In this phase, the foot ispushed and lifted off the ground.

Initial swing is the phase where the hip, ankle, and knee are flexed to begin advancement ofthe limb forward, and clearance of the foot over the ground is created.

During **mid-swing**, limb advancement goes on, and the peak advancement of the thigh is reached.

Terminal swing is the last phase of the gait cycle. The final shank advancement happens, and the foot is positioned for initial foot contact so the next gait cycle can start.

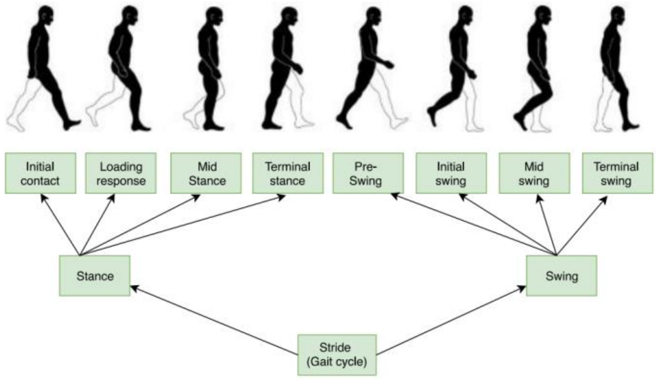

Figure 9. Gait cycle representation [47]

5.1.1.2 Pronation Degrees

The focus of gait analysis is measuring the degree of pronation. Pronation refers to the natural inward roll of the foot while the outer part of the heel strikes the ground. The roll purpose is to absorb the shock for the body and the leg. Pronation is our body's way of optimally distributing the impact force of the heel hitting the ground. There exist three types ofpronation:

Neutral pronation occurs when the weight is distributed evenly, and the shock is absorbed. The foot lands on the outer edge and an inward rolling occur in a controlled manner.

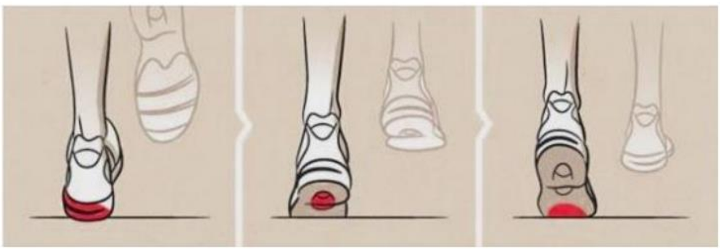

Figure 10. Neutral pronation representation, [3]

Overpronation is when the feet roll inward excessively. Due to that reason, the weight is transferred to the inner edge instead of centering on the foot's ball. Runners with flat feet or low arches usually suffer from overpronation.

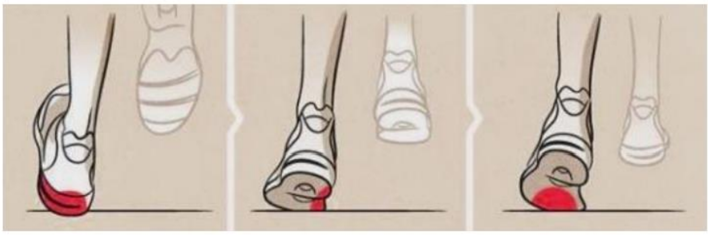

Figure 11. Overpronation representation, [3]

Underpronation (or supination) is usually seen in the runners with high arches. It happens when the outer side of the foot strikes the ground at an angle, steeper than usual, with little or no inward movement. It causes a jarring effect and a massive shock transmission through thelower leg.

Figure 12. Underpronation representation, [3]

Understanding the pronation type helps in selecting the correct shoe type and ultimately toavoid injuries and improve the running efficiency.

Nowadays, smart shoes come with a feature of walking analyzer for analyzing the user's stride, posture, walking pattern, propulsion level (force used to propel the body forward), impact force stability, and many other features. A summary of companies that are fully involvedby putting many efforts into the smart shoe industry is presented in the following sub-chapters.

5.1.2 Mountable Chip on a Shoe

In this sub-chapter, companies as Boltt Sports Technologies and Scribe Labs are shortly introduced. Besides their smart shoes, their particularity is the possibility that they provide to users with regular shoes. In case the wearer is obsessed with a particular type of shoes or does not want to buy some smart ones, these companies provide a mountable chipthat transforms the regular shoes to smart ones.

Boltt Sports Technologies

Boltt Sports Technologies is an Indian startup operated by the same family that runs the sportslifestyle brand Globalite Retail. This startup was founded in 2015, and besides the usual features found in the smart shoes, it offers an integrated virtual health assistant called "B". Boltt partnered with Garmin, the well-known navigation company, which is focused onwearable sensors. Their cooperation results in the creation of sensors that can analyze body data. These shoes are embedded with sensors capable of tracking motion, stride and gait and provide corrective feedback to the wearer.

The Boltt sensor is engineered and powered by patented so-called SDM (Speed and DistanceMonitor) technology with sophisticated chips and accelerometers. It is small and lightweight, and it transfers the stride, leap, and sprint data to the Boltt smartphone app via Bluetooth. A battery with an extended battery life of around 500 hours is also part of the Boltt sensor.

Parameters such as speed, acceleration, workout efficiency, distance, pace, stride length, andcalories are tracked with the Boltt smart shoe. As mentioned above, one of the best features of these smart shoes is the AI voice coach. It gives personalized real-time audio feedback onthe wearer's performance as well as helps in injury prevention. Everyone can set some goalsin the smartphone app, and the smart audio coaching will guide and assist the wearer in meeting all the goals. [4] It is essential to mention that Boltt Sports Technologies provides two smart products, the connected shoes with Boltt sensors embedded in the shoe midsole *(Figure 13* b), and the stride sensor. The stride sensor can be bought by everyone and turn everyone's everyday shoes smart.

Scribe Labs

Scribe Labs is a startup founded in 2013 in San Francisco that works on RunScribe development. RunScribe is a running wearable that offers a 3D view of an athlete's performance, such as contact time, stride rate, and foot strike type. It also provides power metrics that allow the user to monitor and maintain the pace undependably from the terrain changes. Accuracy and precision are the forefronts of this product. [5]

Figure 13. Depictions of the commercial products described in Chapter 5, specifically, the mountable chip on ashoe by ScribeLabs in 5.5.a) and by Boltt Sports Technologies in 5.5.b) [4],[5]

RunScribe is not exactly a smart shoe but a small device that makes all the shoes smart. This small device is mounted on either heels or laces of the shoe. Data transfer to the RunScribe app is done via Bluetooth low energy MCU (Nordic nRF52832). A nine-axis motion sensor MPU-9255 is utilized to tune the motion tracking feature.

5.1.3 Embedded Chip on a Shoe

In the following sub-chapters, an introduction of the companies which are daily researching and investing in the smart shoe industry is carried out. Some of the companies are well-known,whereas some others have recently joined this industry.

Nike

Hyper-Adapt is the smart shoe launched in 2016 from one of the biggest shoe companies worldwide, Nike. The focus of this shoe was mainly basketball players since, during a basketball game, the athlete's foot changes. To improve the performance of an athlete, it is essential to automatically change the fit by tightening or loosening the shoe, which increasesblood flow. The self-lacing feature is the innovative feature of these shoes. Pressure sensorsare placed into the shoe soles. Their function is to sense when the wearer puts the foot insidethe shoe, which triggers an algorithm that allows an automatic lacing process. Some LED lights are present in the shoe design, so the user is alerted when shoes are running out of batteries, or the shoes are tight on foot. One full charge of the battery can last up to two weeks.[7]vv

Figure 14. Commercially available, physical activity tracking and foot ulcer monitoring smart shoes by 5.6.a)Orpyx Medical Technologies, 5.5.b) Altra Running, 5.5.c) Nike, 5.5.d) Digitsole [7][8],[9],[10]

Under Armour

HOVR Phantom and HOVR Sonic are the smart shoes released in February 2018 by the well-known footwear company Under Armour. HOVR Sonic is considered as a better fit for distancerunners, while HOVR Phantom provides a more padded ride due to extra cushioning, and it isdesigned for runners of all distances. In the midsole of these smart shoes, an accelerometer is inbuilt to record all the essential metrics to runners. Pace, distance, steps, stride, and cadence are the parameters recorded from the smart shoe. Map My Run is the app connected to the sensor into the shoe, which helps the wearer to daily monitor the running parameters. The data can also be tracked offline, so the wearer does not have to bring the phone while training. All the data will be stored on the lightweight chip on the shoe until the shoes are syncto Under Armour's MapMyRun app. [11]

Lenovo

The Chinese company, Lenovo, has partnered with Vibram to launch their smart shoes. The shoes use an Intel Curie wearable chip and provide functions like step counting, burned calories, lights up along the shoe bottom when movement is sensed, and contains a customizable 3D-printed insole. A charging panel is also provided, which allows the shoes tobe wirelessly charged. Lenovo smart shoes, despite walking/running parameters, monitor user's health. A 3D scanner, which is placed in the insole of the shoes, tracks the body fat percentage, amount of sweat during a workout as well as wearer's weight. A nice feature of these smart shoes is the LED lights presence at the bottom of the shoes. This feature makesthe running at night suitable, furthermore the lights can interact with the music. There is another futuristic feature of these smart shoes, which is explained in the fun and entertainment sub-chapter. [13]

5.2 Medical

As mentioned, several times throughout this chapter, gait analysis has become an extensively used tool to provide kinematic and kinetic data that are required by physical doctors and therapists for the treatment of their patients.

The significant improvements in gait measurement methods came in the 1970s and 1980s, where electronics were made available -- producing reliable results in minutes. It was after this explosion in technology where engineers and medical domain experts came up with the idea of using these electronics not only to carry out gait analysis measurements but also gather other relevant data related to the wearers' health. By embedding sensors into the shoe, diseases such as diabetes, foot ulcers, Parkinson's, Alzheimer's, or even multiple sclerosis can be monitored and detected in their early stages. This chapter focuses on the advancements that have been recently made in the medical field with respect to these illnesses, respectively.

Diabetes

Diabetes is the illness which prevents the human body from handling blood glucose (sugar), either due to the pancreas' malfunction (Type 1 diabetes, known as insulin-dependent diabetes) or because of the amiss response of the body cells to the insulin produced (Type2 diabetes, also known as non-insulin-dependent or adult-onset diabetes). One of the common diabetes' side effects is sensory neuropathy: the condition in which the human body nerves are damaged, especially the nerves in the foot. The foot is unable to sense injury or change in environmental parameters such as humidity, temperature, and pressure.

Armstrong et al. [24] has reported that 15% of the patients end up further degrading into foot ulcers, where 85% needing surgical amputation due to sensation loss.

Foot Ulcer

Foot ulcers consist of sores on the feet, which increase the lower-extremity amputation by a significant factor. The average duration of pre-ulceration diabetes is more than ten years. Theleading causes of foot ulcers are diabetic components such as neuropathic and vascular complications.

As mentioned in the previous section, sensory neuropathy causes loss of feeling in the foot and leg, and as a result, pressure from shoes, bruises, or any injury to the foot may go unnoticed and further degrade to underlying bone fractures.

Furthermore, vascular complications affect tiny blood vessels that feed the skin. These complications cause the regular pulse in the feet to be undetectable, and the lack of healthy blood circulation results in ulceration. Smoking is another third-party factor that aggravates the vascular disease, thus causing foot ulcers. Due to the surfacing of symptoms in the feet, feet examination is a necessary process that determines feet ulcers diagnosis.

Multiple Sclerosis

Multiple Sclerosis (MS) is an inflammatory disease that chronically affects the central nervoussystem. There are approximately 2.5 million individuals worldwide that suffer from this disease.[25]

The symptoms of MS are mostly related to the decrease in physical activity compared to healthy individuals, such as walking impairment. There have been various studies that have monitored the relation between walking ability and MS, but due to the used methods which involve mostly human memory dependent tasks, they have been deemed error-prone and notaccurate enough.

Apart from these methods, there exist laboratory analysis systems which are considered "thegolden standard", but they require extensive technical support and cannot assess physical activities in patients' everyday life.

Therefore, to overcome these limitations, a lot of ambulatory assessment methods have cometo attention in recent years. They comprise portable devices that permit objective monitoring of walking ability in free-living settings.

Parkinson's Disease

Parkinson's disease (PD) comes as result of the loss of dopamine-producing brain cells. It isknown as a long-term degenerative disorder of the central nervous system affecting the motor system.

Symptoms as shaking, rigidity, slowness of movement, and difficulty with walking appear early in the disease. These symptoms became more common as the disease worsens. [26]

5.2.1 Foot Ulcer Detection

One-third of people with diabetes are experiencing foot ulcers, which is considered the root cause of most foot amputations. The wounds created are quickly worsened in part due to sensation loss - they are not painful, and the patient does not see the doctor until the wound reaches the bone, increasing the risk of secondary infection and gangrene.

Early detection and clinical intervention of ulceration have high importance in preventing ulceration. Early detection of diabetic foot ulceration would improve the health of the people as well as reduce treatment costs. Due to this reason, different companies are highly focusedon detecting, monitoring, and analyzing foot ulceration.

Orpyx Medical Technologies

Orpyx Medical Technologies developed the SurroSense Rx smart insole. This smart insole was the result of a successful collaboration between several universities in Manchester, the United States, and Canada. The smart insole connected to a smartwatch saves diabetic people from foot ulcers. Diabetic peripheral neuropathy or nerve damage is the well-known complication of people who have diabetes. This condition leads to sensation loss where people's feet are at risk of skin breakdown, which is mostly caused by foreign objects in theirfootwear. Late examination of foot ulcers results in an infected wound, which in the worst case, might lead to an amputation. [8]

Orpyx smart insole has ultra-thin sensors to monitor the plantar pressure and provide feedbackvia a smartwatch. Due to sensation loss, it is essential to monitor the pressure applied to thesepeople's feet. The smart insole transmits a wirelessly signal to the smartwatch, which either by vibrating or an audio alert notifies the wearer in case of dangerous foot pressure. The wearer can observe the particular region on the foot where the amount of pressure applied iscritical and use the information to change the behavior and relieve pressure. This method helps the wearer to avoid further damage to the feet. The data saved from the wearer's behavior help the specialists and the researchers to monitor and understand wearers' foot pressure tendencies. An 18-month long study showed that a 71% reduction in the re- emergence of ulcers was observed in the people using the smart insole in comparison to a group where the smart insole was not used.

In different research, it has been shown that an increase in skin temperature compared to the same site on the contralateral limb, is predictive of foot ulceration. A temperature differenceof 2 K or more in the same location of the contralateral feet indicates a high risk of ulceration in the foot with the highest temperature. [27]

InForMed

CMST (an Interuniversity Micro-Electronic Center at Ghent University), and Holst Center in cooperation with RSscan are working on an intelligent shoe sole. The large number of sensors embedded, the high reading frequency rate, and thin and bendable electronics used in this smart sole are its unique characteristics.

Before this cooperation, the Belgian company, RSscan, was focused on the sensor plate device, which was used to measure the pressure profile between the plate and the foot (or shoe if the person is wearing shoes). By using 3D scanners and analyzing the wearers walkingprofile, a personalized sole customized for the wearer's walking profile was produced. As a next step, InForMed started working on the smart shoe, where sensors were embedded in thesole. By analyzing the readings taken inside the shoe rather than underneath it, the wearer can track and obtain precise information about walking patterns over a long period.

The sensor sole consists of two layers, the sensors layer and the pressure-sensitive one. A resistance reduction and a current flow increase through the sensors are observed when pressure is exerted on the pressure-sensitive layer. As a result, the pressure difference is measured. There are two potential technologies proposed for the smart sole. The first one is proposed from CMST, where polyimide is used as a carrier for its flexible electronics with laminated copper on both sides. At the same time, Holst Center uses thermoplastic polyurethane and prints silver structures on it using roll-to-roll techniques. [31]

CHAPTER 6

ENERGY CONSUMPTION

In the case of an active system into the shoe, lithium-ion batteries are considered a good candidate. Among the existing batteries, lithium-ion ones are widely used in portable electronicdue to their long cycle life, relatively safe and mature production technology, and the most important their high energy density. [48] In the last few years, the demand for wearable electronic devices has been increased, and the flexibility of energy storage devices isbecoming more and more crucial. [18] Flexible lithium-ion batteries have been developed, and they are commercially available. Besides their flexibility, researchers worldwide are working to improve other key performance metrics such as cycle life, safety, manufacturing cost and energy density. Zhang et al. fabricated a polymer-free fiber-shaped lithium-ion battery with a high gravimetric energy density of 98.6 Wh/kg and a relatively high-power density of 445.4 W/kg (both calculated based on the mass of electrode), at a current density of 0.5 A/g. On theone hand, flexible lithium-ion batteries provide enough flexibility to be used in wearable applications, but on the other hand, their energy density is considered far lower than non- flexible lithium-ion batteries which is usually greater than 200 Wh/kg (based on the mass device). [22]

In this research, two energy consumption scenarios are analyzed and explained as follows.

In the first scenario, a commercial lithium-ion polymer battery, a microcontroller, temperature,acceleration, and pressure sensors are considered. Typical batteries have 3.7 V output voltage along with a capacity of several hundred to thousands mAh. We considered a 1200 mAh battery, with a 23 g total weight, including packaging and connections. Thus, the stored energyis 4.4 Wh. The energy consumption of Bluetooth, together with sensors, is less than 30 mWh.It is calculated that such a system can last around 150 hours or more than 6 days.

In real applications, the runtime could be extended by choosing low-power mode for data transmission, partial switch off communication and sensor features, or even hibernating the whole system.

In the second scenario, a commercial flexible lithium thin-film battery is considered instead ofthe lithium-ion polymer battery, where the amperage equals 28 mA, and the total weight 0.86g - including packaging and connections. The output voltage of this battery is 3 V, so the energy stored consists of 0.08 Wh. Keeping in mind that the consumption of the system (Bluetooth and sensors) is the same as in the first scenario, it is calculated that the amount oftime that this system can last without charging is little more than 3 hours.

CHAPTER 7

METHODOLOGY

8.1 Components and Supplies

Arduino

The Arduoino board used for this project is called Arduino MKR 1000 WiFi. The reason behind this choice is its compatible size. This board is widely used in IoT projects where size and weight play a crutial role. It provides a simple user experience, and it is straight forward to combine it with pressure and acceleration sensors in order to analyze the gait analysis.

Force sensitive resistor

In this project the most suiteable sensors to analyze the physical pressure are force sensitive resistors. There is a wide variety of models but 402 FSRs model is the one used in this thesis. FSR 402 is cost effective and simple to use, but its drawback is the accuracy.

To get almost the full body weight pressure, three sensors are embedded in the shoe insole. Two of them are in the front part of the insole and the third one is located in the back part of the insole.

Resitor

To protect the FSRs sensors as well as to scale the results readings in the desired scale, three 10K ohm resistors are used.

Accelerometer

To measure the acceleration and motion of the foot, a 16G ADXL345 acceleration sensor is used. Its size is competiable with IoT devices, and it is also straightforward to be connected with the Arduino board.

8.2 Images of the Components

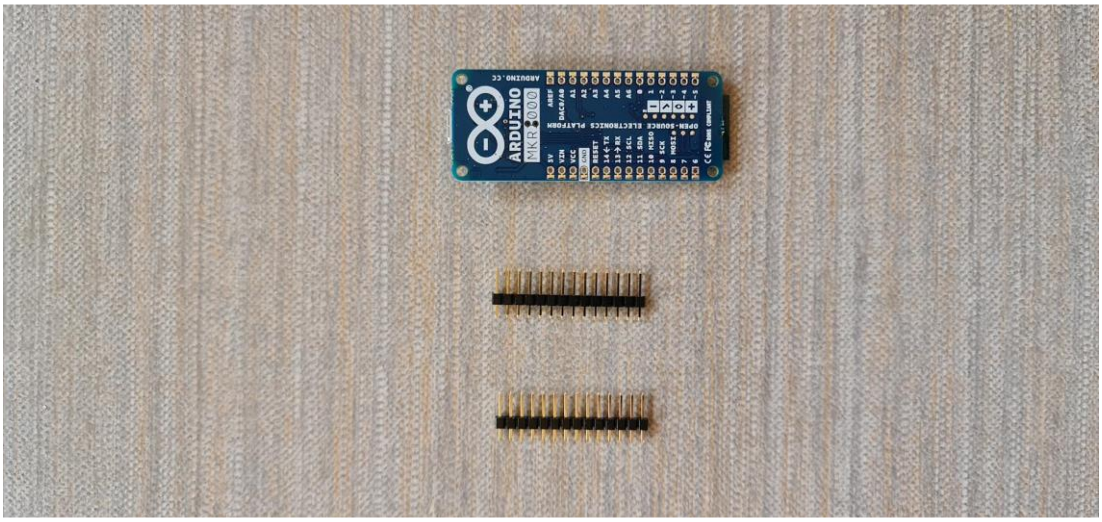

Figure 15. Arduino MKR1000 front view

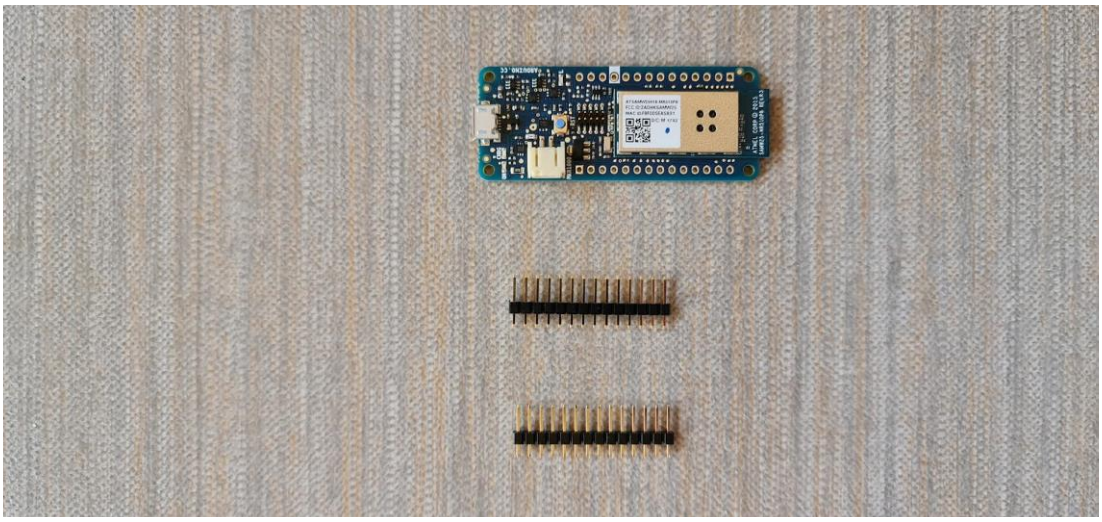

Figure 16. Arduino MKR1000 back view

Figure 17. 10K ohm resistors

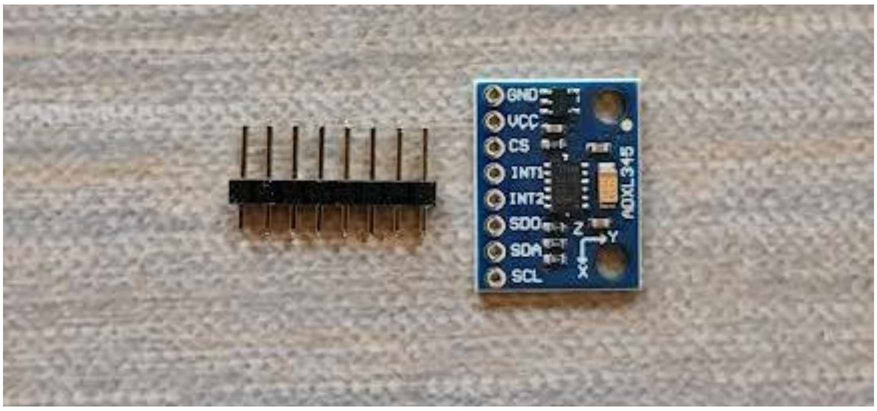

Figure 18. 16G ADXL345 Accelerometer front view

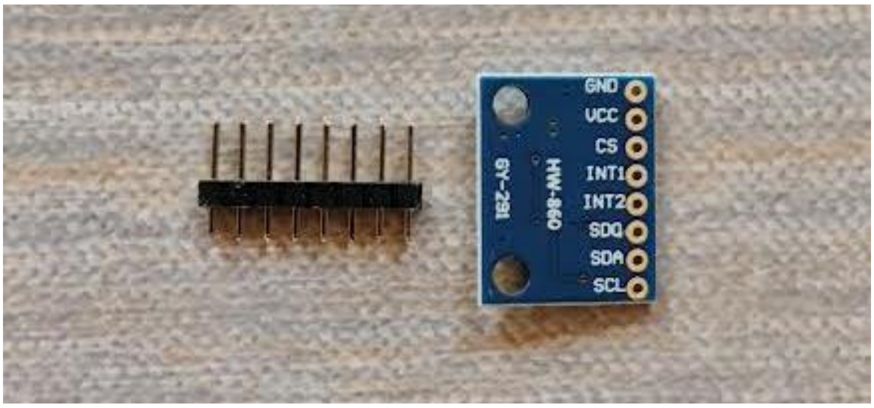

Figure 19. 16G ADXL345 Accelerometer back view

Figure 20. Pressure sensor front view

Figure 21. Pressure sensor back view

8.3 Experimental Results

A detailed gait analysis of the wearer is shown in the following sub-chapters. Three pressure sensors (FSR 402) which are placed in the shoe insole analyze the pressure distribution while walking or running. Furthermore, an acceleration sensor (16G ADXL345) provides the acceleration of the wearer in three axis x, y, z.

8.3.1 Pressure Distribution

After collecting all the data from the pressure sensors, further analysis is provided with the help of thinger platform. A better data representation is shown in form of the graph so the wearer can see his feet pressure distribution and create a clearer understanding about the way he/she walks or runs.

Figure 22. FSR Analogue output

As shown in the (*Figure 22*), three FSR sensors output are represented in three different colors. For each sensor the output values differ depending on the position of the foot. If the wearer puts more pressure on the upper part of the shoe insole, an output value increase of the FSR sensors attached to that part is detected.

8.3.2 Acceleration

For a more precise gate cycle, the accelerometer data is shown in the following graph. A detailed information about acceleration is provided by gathering data from x, y, z axis of the acceleration sensor.

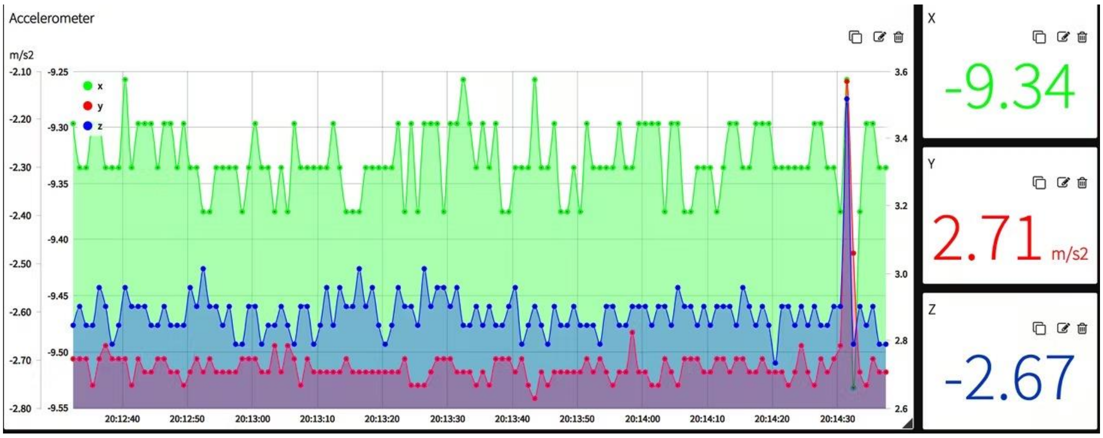

Figure 23. Output of the accelerometer

8.4 Hardware and Software of the Final Product

8.4.1 Hardware

A block diagram of the final product with all the final components is presented in the picture below:

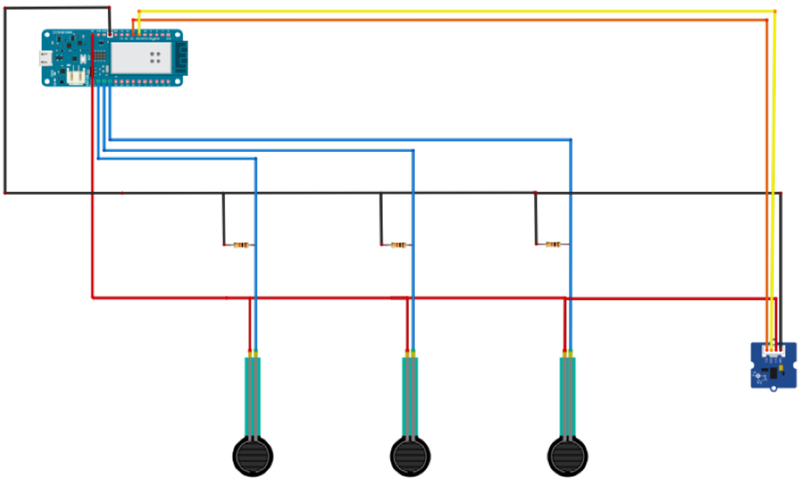

Figure 24. Schematics of the final product

8.4.2 Software

The purpose of this code is to visualize all the results gathered from the sensors. Thinger.io Wi-Fi library is used. The connection is set up via the line below:

Thinger Wifi101 thing (USERNAME, DEVICE_ID, DEVICE_CREDENTIAL);

All the arguments are obtained from the account created in Thinger.io platform. As a next step a setup() function is called in order to establish the serial connection. After all the inicialization of all variables are done, in order to measure force we have to declare a function called pressure. This function reads all the values from FRS sensors and gives the output in the serial console. These values are stored in the local variable frsReading. It is important that before returning them into an array, these values are scaled with the help of the map function. As a results, each FRS sensor has a unique string like FRS1voltage, FRS2voltage and FRS3voltage. As a next step, a function called newton is used to convert the voltage to a force in Newtons. These results can be observed in the variables called frsForceArray. There are three final values which are sent to the output channel. Furthermore, a function called weight is used in order to return force into weight (grams).

To measure the acceleration Wire.h, Adafruit_Sensor.h and Adafruit_ADXL345_U.h libraries play a crucial role to provide a communication with the SDA and SDL pin. As we know acceleration is measured on three axes, so three global variables are declared, x.y and z. To obtain the acceleration sensor results, a function called accelerometer is executed. All the data gathered from x, y and z are transferred to the output channel.

A lambda function is used in order to send all the data to the visualization display in Thinger.io. The following line is an example of the force data gathered from the sensors transferred to the Thinger.io platform for a further visualization:

thing["newton"] >> [](pson & out)

As a last step a loop function is used where thing.handle() is called and is looped continuously. This is used to continiusky get information from all the sensors.

For more information the full code used is provided below:

```
#define _DEBUG_
#include <WiFi101.h> //Thinger
#include <ThingerWifi101.h> //Thinger
#include <Wire.h> //Accelerometer
#include <Adafruit_Sensor.h> //Accelerometer
#include <Adafruit_ADXL345_U.h> //Accelerometer

#define USERNAME "yourUsername"
#define DEVICE_ID "yourDevice"
#define DEVICE_CREDENTIAL "yourCredential"
#define SSID "yourSSID"
#define SSID_PASSWORD "yourSSIDPassword"

Adafruit_ADXL345_Unified accel = Adafruit_ADXL345_Unified(12345);
//Accelerometer

int x = 0; //Reset to 0
int y = 0;
int z = 0;

//*FSR sensors*/
#define noFSRs 3 // Number of FSRs connected
#define FSR1 A1  //Analogue ports
#define FSR2 A2
```

```
#define FSR3 A3

float fsrVoltageArray[3];       // The analog reading converted and
//scaled to voltage as a floating point        //number
float fsrForceArray[3];     // The force in Newton
float fsrWeightInGramsArray[3]; // Weight converted to grams

int  pinArray[3]     = {FSR1, FSR2, FSR3};    // The pin ID for the
//three devices
float forceMaxArray[3]   = {100.0, 100.0, 100.0}; // Maximum forces
//supported

float million = 1000000.0; // Unit for "1/micro
float conversionToKgrams = 1.0/9.80665;

long K     = 1000;
long R     = 10*K;    // R in K Ohm
long Vcc    = 5000;    // 5V=5000mV, 3.3V = 3300 mV
float voltageMax = 0.98 * Vcc; // Maximum voltage set to 95% of Vcc. Set
//the force to the maximum beyond this         //value.

ThingerWifi101 thing(USERNAME, DEVICE_ID, DEVICE_CREDENTIAL);
//Call to set up WiFi function

void setup(void) {
  Serial.begin(115200);
  thing.add_wifi(SSID, SSID_PASSWORD);
```

```
if(!accel.begin()) {   //Initialise the sensor
  Serial.println("No ADXL345 detected.");
} else {
  accel.setRange(ADXL345_RANGE_16_G); //Range for this sensor

  thing["accelerometer"] >> [](pson& out){
      sensors_event_t event;
      accel.getEvent(&event);
      out["x"] = event.acceleration.x;
      out["y"] = event.acceleration.y;
      out["z"] = event.acceleration.z;
  };
}

 /*FSR sensors*/
thing["pressure"] >> [](pson & out) {
  out["FSR1"] = analogRead(FSR1);
  //    Serial.print("FSR1:");
  //    Serial.println(analogRead(FSR1));
  out["FSR2"] = analogRead(FSR2);
  //    Serial.print("FSR2:");
  //    Serial.println(analogRead(FSR2));

  out["FSR3"] = analogRead(FSR3);
  //    Serial.print("FSR3:");
```

```
  //    Serial.println(analogRead(FSR3));
};

thing["voltage"] >> [](pson & out) {

  for (int FSR = 0; FSR < noFSRs; FSR++) {

    fsrVoltageArray[FSR] = 0.0; //Reset values upon entry
    fsrForceArray[FSR]   = 0.0;

    int fsrPin   = pinArray[FSR];
    int fsrReading = analogRead(fsrPin);

    fsrVoltageArray[FSR] = (float) map(fsrReading, 0, 1023, 0, 5000);
  } //End of loop over FSR's

  out["FSR1voltage"] = fsrVoltageArray[0];
  out["FSR2voltage"] = fsrVoltageArray[1];
  out["FSR3voltage"] = fsrVoltageArray[2];
};

thing["newton"] >> [](pson & out) {
  for (int FSR = 0; FSR < noFSRs; FSR++) {

      // The value of the force F as a function of the voltage V is
///computed as: F(V) = (Fmax/Vmax) * V
```

float force_value = (forceMaxArray[FSR]/voltageMax) * fsrVoltageArray[FSR];

// Three situations are distinguished:

//

// 1. If V is too close to the maximum (as defined by voltageMax //), the force can

// go to infinity. This is avoided by setting it the maximum //value as soon as it is higher than our threshold voltageMax.

//

// 2. If the computed force F is too small, we set it to zero to // avoid noise effects.

//

// 3. In all other cases, we take the logarithmic value to

//reduce the sloop and better distinguish small changes.

if (fsrVoltageArray[FSR] < voltageMax) {

// V is not too high in this branch

if (force_value <= 1.00) {

fsrForceArray[FSR] = 0.0; // Force is too small, set it to // zero

} else {

fsrForceArray[FSR] = log10(force_value); // Value is okay, //take the log of //this

}

```
} else {

    // Cap the force if the voltage is too close to Vcc (for Vcc //it would be infinity)

    fsrForceArray[FSR] = log10(forceMaxArray[FSR]);

    Serial.print("Cut off activated for FSR = "); Serial.println(FSR);
  }

} // End of loop over FSRs
  out["FSR1newton"] = fsrForceArray[0];
  out["FSR2newton"] = fsrForceArray[1];
  out["FSR3newton"] = fsrForceArray[2];
}; //End of thing

thing["weight"] >> [](pson & out) {

//Straightforward computation to convert the force in Newton to the weight in grams

for (int FSR = 0; FSR < noFSRs; FSR++) {
  fsrWeightInGramsArray[FSR] = fsrForceArray[FSR] * conversionToKgrams * 1000.0;
}
  out["FSR1weight"] = fsrWeightInGramsArray[0];
```

```
    out["FSR2weight"] = fsrWeightInGramsArray[1];
    out["FSR3weight"] = fsrWeightInGramsArray[2];
  }; //End of thing
} //End of setup

void loop(void) {
  thing.handle();
}
```

CHAPTER 10

CONCLUSIONS

Pressure, acceleration, and temperature sensors are the typical types of sensors embedded into the smart shoes, measuring physical activity parameters either directly or indirectly via these sensors. Besides sensors, other electronic components such as a microcontroller, Bluetooth, and battery are embedded in the shoe.

Based on our literature review, we conclude that the research happening nowadays for smartshoes is based almost entirely on active systems. The presence of a battery is a must in suchsystems, where many parameters are monitored, and many features are provided. There arefewer restrictions in comparison to both passive and semi-passive regarding new features andnew sensors added.

On the other hand, the main drawback of active systems is the continuous need for charging.Mainly driven by the demands from mobile communication and to some extent from smartwatches and fitness bands, research and development are aiming for high-tech batteries with low energy consumption and long run-times. Another pioneering feature provided for smart shoes is wireless charging, which has been very well-received by technology enthusiasts.

In our research, we have also explored the possibilities for smart shoes without battery. Embedding a passive RFID tag into the shoe can provide the wearer with several smart features. Besides fraud protection, identification even to avoid mixing left/right or different sizes in one pair, there is also the possibility for information storage, e.g. for recycling or waste- management information. The most crucial advantage of embedding passive RFID tags in shoes is that there is no need for maintenance and charging.

The advantages of RFID tags consist of low cost, negligible weight, and long lifetime if placedin a gentle environment. On the other hand, the number of sensors, features, and parameterstracked is restricted. The absence of an active antenna means the passive RFID tags have an extremely short frequency range, which results in a short communication range. Without an onboard battery, passive tags have limited storage. The process of reading the informationstored in the tags requires a reader, which needs to be powered as well. Besides, the fact thatdifferent companies are using different methods to encrypt the information stored in the tags,the privacy of RFID tags remains a critical topic.

In case of demand for sensors on a passive RFID tag, an RFID SAW tag is recommended. Aspointed out in chapter 3, these tags can be used as a sensor, and they are inexpensive, easyto fabricate, small, robust, sensitive, and most importantly, they can work without a local powersource. In principle, SAW devices can operate as temperature, pressure, humidity, bio-, and chemical sensors, but practically only temperature and pressure SAW devices are commercially available.

In conclusion, besides the number of sensors and high-tech features, active systems providethe wearers with a lot of personalized feedback in a user-friendly method. Every customer canmonitor, analyze, and compare the data tracked just by one click on the app provided by respective companies. There seems to be another big issue of passive systems embedded into the shoe, where although there is enough information stored, a regular wearer will not beable to access it without an RFID reader.

The estimated number of patents in smart shoe development in the range of 100 000 depending on the exact search query. Regarding smart shoes' applications, it can beconcluded that their most prominent application field is sports, where parameters such as distance, speed, acceleration, steps, stride, pronation, cadence, pace, calories burned, and workout efficiency are tracked. A combination of machine learning and artificial intelligence algorithms, together with sensors embedded into the shoe, are taking the impact of the smartshoe industry to a whole new level. Personalized real-time audio feedback for coaching is considered cutting-edge technology in both professional and consumer sports.

Moreover, in the field of medicine, scientists have emphasized the importance of the relationship between gait analysis and neurological disorders, where diseases such as Parkinson, atypical Parkinson, and Alzheimer's can sometimes be predicted and monitored via smart shoes. Early detection of neurological disorders is a crucial parameter in the successful treatment of these patients. By measuring the pressure applied to the foot sole, smart shoes can generally aid patients a lot in revealing important information about the disease, but for patients in more severe conditions, they may as well be a necessity when it comes to foot ulcer monitoring.

Extensive usage of smart shoes is also observed in fun and entertainment, as well as in E- sports. The footwear industry is keeping pace with the development of E-sports; besides wearable devices such as smart suits and VR glasses, smart shoes are trying to get the wearers to immerse themselves in the virtual world. Numerous applications, such as performance shoes (combining lights with music), slippers parking themselves, etc., are becoming more and more attractive and fashionable for the customer.

Based on the presented survey, there are several applications for passive sensor and identification systems. However, the most trending and assumingly growing applications in sports and medicine, together with machine learning and artificial intelligence as key drivers, require most likely more and different data, suggesting that active sensor systems are the wayto go.

CHAPTER 11

CONTRIBUTION

In this thesis, a literature review of the recent developments in the smart shoe market carrying out an analysis of high-tech features and electronics components embedded into the shoe are provided. Furthermore, patent research together with the existing smart shoes in the industry are examined.

The smart shoe industry nowadays is focused on the active system where a battery and several sensors are used to provide all the data analyzed. As part of this research, a detailed analysis of the most important sensors that can be used is given. An important role in this research is finding the optimal position of each sensor as well as integrating the latest high tech battery systems.

A thorough investigation where a completely passive smart shoe with passive sensors is analyzed as part of this thesis. A crucial role of the passive smart shoes is finding different sensors that can gather as many data as possible without the need of a battery.

An active prototype with Arduino, pressure, and acceleration sensors, where different features are analyzed while walking will be part of this research.

11.1 Future Work

As concluded, the recent years have shown a surge in the footwear market demand. There are already several features that can be measured with the existing smart shoes but as technology is evolving, the number of features can be increased. In the future, all the sensors and other electronic components may have a smaller size and lighter weight, which means more sensors can be embedded inside the shoe insole and still not effect the wearers performance. Batery lifetime and capacity is a hinderer at the moment, but due to everyday research happening in battery technology, it will be improved in the near future. Flexible thin film batteries are a potential solution which might bring a revolution in the wearable technology and especially in the smart footwear market.

Another potential improvement that is expected to happen in the footwear technology is implementation of AI and ML algorithms. Analyzing all the data with sophisticated AI and ML algorithms is already possible but a more accurate and optimal data analyzation will be possible in the near future. A futuristic idea is combining several wearable devices and with the help of these algorithms getting the most appropriate personalized advice to improve the wearers life.

Real time coach assistant is a future research scenario that can be possible just by using smart shoes and a pair of headphones. All the sensors and electronic components combined with AI and ML algorithms might provide real time coaching while doing sports and presenting the analyzed result in the wearers headphones.

Smart footwear industry has room for a lot of research and gives opportunities for numerous high-tech features' implementation. In the future, smart shoes will have a high impact in our everyday life and will significally improve our life quality.

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